

Cost Optimization of a Nearly Net Zero Energy Building

A case Study

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Abstract— The Net Zero Energy Building concept has received increasing attention in recent years, until becoming part of the EU policy on energy efficiency in buildings. Recently, a very important focus on cost-effectiveness has also been introduced. In particular, an EU regulation of 16 January 2012 establishes a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. The big challenge is to understand how much designers should rely on energy efficiency measures and when instead they should start to apply renewable energy technologies. The study presented in the paper is focused on the synergy between energy–efficiency in terms of envelope and renewable energy utilization to achieve a balanced energy budget over an annual cycle, minimizing at the same time the investment costs. An analysis adopting the cost optimality methodology on a residential case study has been carried out. Coupling TRNSYS 16, a transient system simulation tool, and GenOpt®, an optimization program, an optimization analysis has been performed in order to find a cost-optimal energy performance and to detect the best balance in terms of investment costs in envelope and in energy generation.

Keywords- Zero energy building; Net zero energy buildings; Cost optimality analysis.

I. INTRODUCTION

The Nearly Zero Energy Building concept is a key issue for the next decade in Europe and not only. This is clearly pointed out in the Directive 2010/31/EU, which is the main EU-wide legislative instrument to improve energy performance in buildings [1]. Under this Directive, the Member States must apply minimum requirements as regards the energy performance of new and existing buildings and ensure the certification of their energy performance. In particular, the Nearly Zero Energy Building standard will become mandatory in 2019 for public buildings and in 2021 for private ones. Moreover, Lombardy Region (Italy) anticipated this deadline to the end of 2015 with a regional law issued on 18 April 2012 [2].

The EU directive requires nearly zero energy buildings, but since it does not give minimum or maximum harmonized requirements as well as details of energy performance

calculation framework, it will be up to the Member States to define what the concept of Nearly Zero Energy Building stands for [3].

As highlighted by Marszal et al. [4,5] in the literature review of ZEB definitions, only few out of the reviewed definitions emphasize the importance of employing energy efficiency measures before using renewable energy sources. Therefore, Marszal et al. conclude that, in order to ensure that Net ZEBs are also very energy efficient buildings, a good solution could be to include a fixed value of maximum allowed energy use in the Net ZEB definition. However, when considering the Net ZEB concept, a new problem arises, i.e., to what level should we decrease the energy use by means of energy efficiency measures before the implementation of renewable energy sources [6]?

This paper treats the Net Zero Energy Building concept focusing in particular on the balance between envelope energy performance and energy production by Photovoltaic (PV) in terms of cost optimality. The aim is to investigate the existence of a compromise between a good envelope performance and investment cost while ensuring the Net Zero Energy Building target. This target is here treated according to the definition proposed by K. Voss and al. for which in Net ZEB total primary energy use, including building energy use, on a yearly basis is covered by energy produced on-site and building-connected renewable energy sources [7].

Currently, the cost optimality concept has been poorly investigated from this point of view and focused to obtain directions for residential building design. In the literature just a few national examples have been proposed by Aalborg University and Aalto University up to now; no data are available on residential building in the north weather [8,9, 10].

II. REFERENCE BUILDING

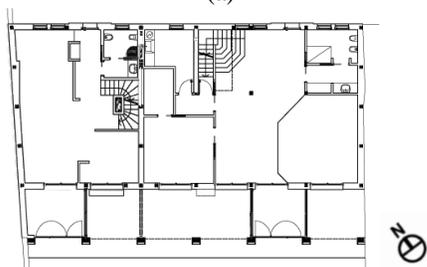
The present paper refers to a specific case study that is an existing residential building sited in Colognola, a small town near to Bergamo in the northern part of Italy, consisting of two independent homes sharing a party wall [11].

The northern façade, fully integrated with the historical context, is opposed to the South side towards the garden,

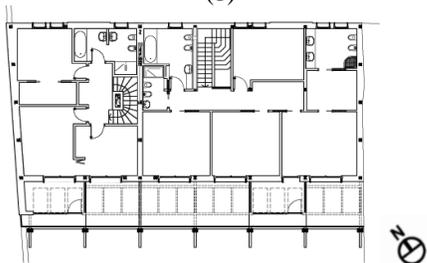
where sunscreens, loggias and conservatories act as thermal collectors. The West side has no openings and is characterized by a ventilated skin of timber slats to avoid summer overheating of the envelope surface. Figure 1 shows picture, plans and cross section of the building.



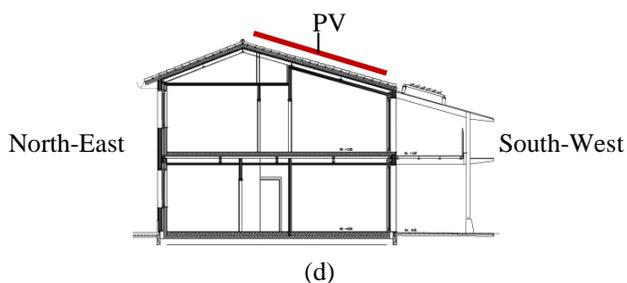
(a)



(b)



(c)



(d)

Figure 1. The figure shows the picture (a), plan of the first (b) and second floors (c) and cross section of the building (d).

The envelope is based on a lightweight, stratified, dry-assembled construction system. This delivers a very high thermal performance, with very good behavior both in winter and summer. This building has been rated as “A - Gold” according to KlimaHaus protocol.

The heating system is based on a high-efficiency natural gas condensing boiler (efficiency at 30% partial load = 109%) combined to a radiant floor system working at low

temperature. This system is characterized by flow temperatures of 28°C and 40°C, modulated by external probe and local temperature regulation in each room. In order to minimize the energy consumption and to ensure the necessary hygienic conditions inside the rooms, a mechanical ventilation system is provided to each of the two independent flats. Each unit is equipped with a cross-flow heat exchanger with 90% efficiency. Solar collectors provide more than 50% of the required domestic hot water.

The areas and U-values for both opaque and glazed parts of the building envelope are summarized in Table 1.

TABLE I. GEOMETRICAL AND PHYSICAL PROPERTIES OF THE ENVELOPE “AS BUILT”

	<i>U-value</i> [W/m ² K]	<i>Area</i> [m ²]
External wall:		
South-West	0.12	70.8
South-East	0.12	74.0
North-West	0.12	77.5
North-East	0.12	128.0
Floor	0.16	220.0
Roof	0.09	245.7
Window:		
South-West	0.95	55.2
North-East	0.95	20.4

Sensible heat gains from equipments, including also heat gains due to artificial light, have been evaluated supposing the building occupancy. In particular, during the weekend a continuous building occupancy has been supposed. 100% occupancy corresponds to four people.

A typical working day occupancy is summarized in Figure 2.

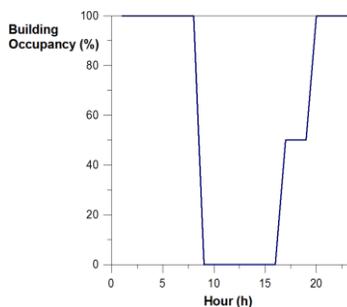


Figure 2. Occupancy schedule of the simulated building – week day.

III. NUMERICAL MODELLING AND BUILDING ENERGY PERFORMANCE

The TRNSYS 16 software [12] was used in order to perform a transient simulation of the energy behavior of the

building. Trnsys model validation has been widely discussed in the literature [13].

The weather data of Bergamo was adopted for the simulation. The city lies 249 m above sea level, with a latitude of 45.70°N and a longitude of 9.67°E. The annual total solar radiation in Bergamo is 1,398 kWh/m² with approximately 1,900 hours of sunshine.

The heating system is operating between November and March; the cooling system is set to activate summer months only when indoor temperature is higher than 26°C, while the threshold for humidity control is 60% independently from the indoor temperature. In the remaining months, the building is in free-running condition.

The results related to the “as built” configuration show that the heating and cooling demand is equal to 13 kWh/m²y.

In order to define the best envelope performance in terms of cost for the specific case study, TRNSYS was coupled with GenOpt, an optimization program for the minimization of a cost function.

GenOpt is designed for finding the values of user-selected design parameters that minimize a so-called objective function. The objective function is calculated by an external simulation program, in this case TRNSYS.

The Hybrid Generalized Pattern Search Algorithm with Particle Swarm Optimization Algorithm implemented in GenOpt was used [14]. Such an algorithm is a hybrid global optimization algorithm that starts by doing a Particle Swarm Optimization (PSO) on a mesh for a user specified number of generations $n_G \in \mathbb{N}$. Afterwards, it initializes the Hooke-Jeeves Generalized Pattern Search (GPS) algorithm using the continuous independent variables of the particle with the lowest cost function value. The optimization problem has continuous and discrete independent variables, then the discrete independent variables are fixed at the value with the lowest cost function value by the GPS algorithm [14].

This approach is summarized in Figure 3.

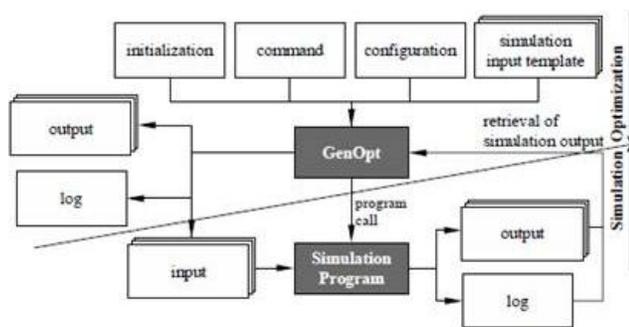


Figure 3. Interface between GenOpt and the simulation program (TRNSYS 16) [13]

GenOpt automatically rewrites the input files for TRNSYS at each iteration changing the variables taken into account. After this, it runs the simulation program, reads the output value of the function to be minimized from the simulation result file and then determines the new set of input parameters for the next run. The whole process is

repeated iteratively until a pre-defined criterion of convergence is fulfilled or a maximum number of iterations is reached [14].

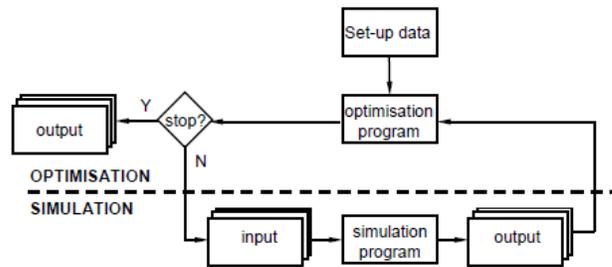


Figure 4. Combined simulation-optimization [15]

The parameter taken into account to achieve low energy loads is the U-value of the envelope. Other parameters, like window to wall ratio or building orientation, have not been considered not only to ensure the necessary design freedom, but also because they scantily affect the energy response of the building. This consideration is the result of sensitivity analysis done before to assess which are the parameters that mainly govern the building energy behavior [11].

In the sensitivity analyses done, have been considered the U-value of the roof and walls, the building orientation, the glazing fraction of the wall and the wall concrete thickness. Starting from the “as built” situation each of the mentioned parameters were changed keeping all the others at the initial values.

Looking at the results represented in Figure 5, it is possible to observe how a change from 30% to 80% of the glazing fraction causes a change of less than 2 kWh/m²y in the annual combined consumption (H+C), a variation from 3 to 8 cm in concrete thickness and a 360° rotation of the building both bring to a variation of about 1 kWh/m²y and finally a change from 0.1 W/m²K to 0.4 W/m²K in the U value of the roof and wall brings an annual combined load variation larger than 7 kWh/m²y.

In this way, it is possible to conclude that the U-value of the envelope is at the same time the easiest parameter to control independently of architectural design choices and the most decisive one. Considering this value as a variable, an optimization process has been run by considering the global cost of the construction as the function to minimize. The global costs here considered take into account envelope investment costs and the energy costs depending on the primary energy demand. The energy costs were calculated according to the EN 15459 standard in order to consider market movements with respect to energy price increases for the analyzed period (20 years) [16]. EN 15459 regards the economic evaluation procedure for energy systems in buildings and is also used by the Commission delegated regulation (EU) N° 244/2012 of 16 January 2012 which establishes a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements [17].

Keeping a fixed thermal transmittance value for windows, equal to 0.95 W/m²K, the thickness of the façade

insulation was changed in order to vary its U-value from 0.09 W/m²K to 0.35 W/m²K.

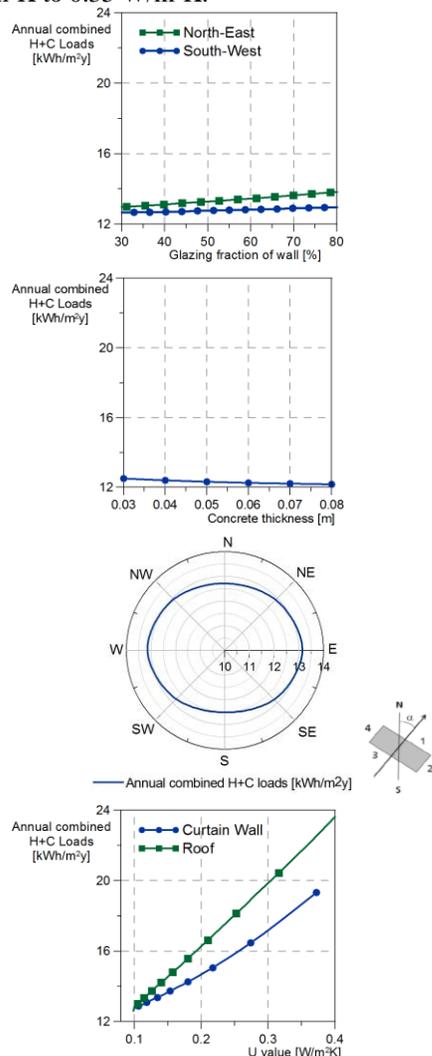


Figure 5. Results of sensitivity analyses.

The optimization performed considering the global cost as the cost function allowed us to define the curve that represents the relationship between global costs and primary energy demand (Figure 6).

The graph shows that the minimum point of the Cost/Energy demand curve does not coincide with the minimum point in terms of primary energy demand. This means that to invest overly on the envelope performance is not the best choice if considering only the cost optimality point of view [18].

It is worth noting that only the energy used for the building operation has been taken into account; the energy embedded in the building construction was not considered.

Since the European regulation requires nearly zero energy building starting 2020 but does not provide any limitation in terms of energy performance related to cost analyses, further investigations have been done to find the best investment balance between envelope and energy production by renewable sources.

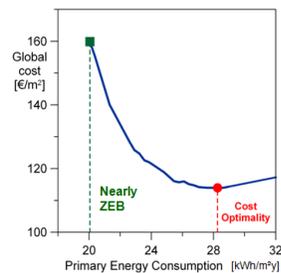


Figure 6. Cost curve in function of envelope performance accounting a study period of 20 years.

IV. TOWARDS NET ZERO ENERGY BUILDINGS

The next step of the study was to assess the effect of PV technology to achieve nearly ZEB status. To predict the behavior of PV panels was added an additional component (type 194) to TRNSYS building model.

TRNSYS PV model used is a five-parameter model based on an equivalent circuit of a one diode-model (Figure 7). This approach is useful to predict the energy production of monocrystalline PV power plants and requires very few parameters [19,20,21,22].

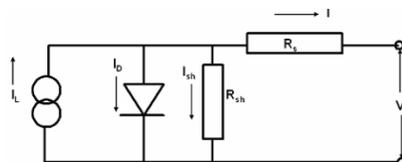


Figure 7. Equivalent circuit for the 5-Parameter model [21].

A new optimization process has been run considering both the envelope (U value) and the PV surface on the roof as variables. The global costs during the 20 year period have been again adopted as the function to minimize.

The PV panel here considered is a high performance panel characterized by cells efficiency higher than 20% and a nominal power of 330 W [23].

In the global cost evaluation, also the costs of the PV panels have been considered as well as the PV energy production that is subtracted from the primary energy demand if production and demand happen at the same time, while when production is larger than demand the remaining energy is sold to the grid.

Figure 8 shows that also in this case the minimum point in terms of cost does not coincide with the minimum point of the primary energy demand.

In this case, the optimization takes into account the actual situation of Italian government incentives (IV Conto energia [24]), which imply a considerable reduction of the global cost. Also in Figure 8, we present a comparison with the cost-energy demand curve previously discussed (Figure 6).

A set of optimizations was run to study the different results obtained by considering different values of government incentives for each kWh of produced sold to the grid. This price was considered variable from 0 to 0.25 €/kWh.

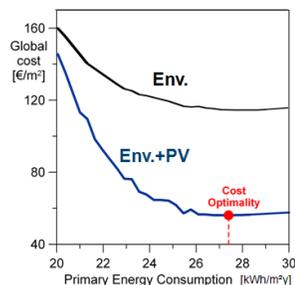


Figure 8. Cost curve in function of envelope performance and energy production by BIPV accounting a study period of 20 years.

Figure 9 summarizes the results focusing on the envelope, PV and global costs of the cost optimal solutions while Table 2 highlights, for the same solutions, the annual heating (EP_H) and energy (H+C) demands together with the PV energy production.

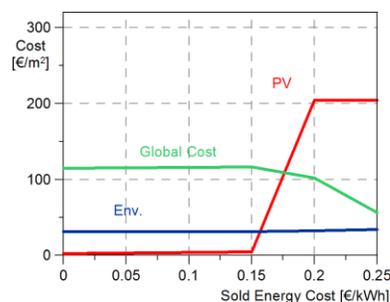


Figure 9. Results obtained by considering different values of government incentives.

TABLE II. ANNUAL HEATING (EP_H) AND ENERGY (H+C) DEMANDS WITH THE ENERGY PV PRODUCTION

Sold Energy cost	EP_H of optimal solution	Heating+ Cooling demand of optimal solution	PV energy product of optimal solution
[€]	[kWh/m ² y]	[kWh/m ² y]	[kWh/m ² y]
0	16.21	28.26	0.64
0.15	16.21	28.26	0.64
0.20	15.85	27.84	57.35
0.25	15.42	27.40	57.35
0.30	15.02	26.99	57.35

The graph shows that the envelope solution optimizing the global cost is not dependent from the government incentives: as a matter of fact, the line representing the envelope investments is quite horizontal.

This envelope solution corresponds to a building that is able to guarantee an annual energy demand (H+C) of about 27 kWh/m²y and an energy heating demand (EP_H) of about 15 kWh/m²y.

Increasing the price of sold energy, the optimized envelope is still the same, but the global cost optimal

solution tends to have increased PV investment thus decreasing the global costs.

Considering the case in which the customer can not sell his overproduction of energy providing it for free to the grid (sold energy cost equal to 0), it is possible to observe that the cost optimal solution is not a net zero energy solution.

In this case, in order to ensure the net zero energy performance to the building it is necessary to provide energy by means of further PV panels thus moving away from the cost optimal solution.

Looking at the primary energy demand for space heating, Figure 10 shows a comparison of the situations for different types of envelope solutions. The 45° line represents a NZEB situation since the EP_H is equal to the energy production. Moving from the horizontal axis that represents the situation in which no PV panels are available, the figures represents which is the PV panel investment aimed to reach the NZEB solution for different building which envelope is rated in different classes according to Lombardy standard. For each of those solutions also the PV and envelope global costs are reported.

It is worth noting that a building rated in class A according to the energy performance scheme of Lombardy is the choice which is able to guarantee the lowest global cost.

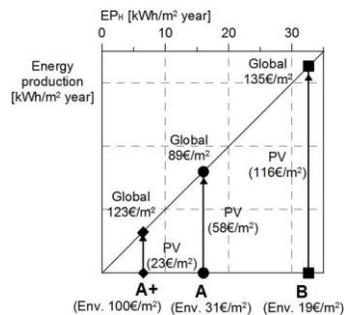


Figure 10. Cost comparison for different type of envelope solutions.

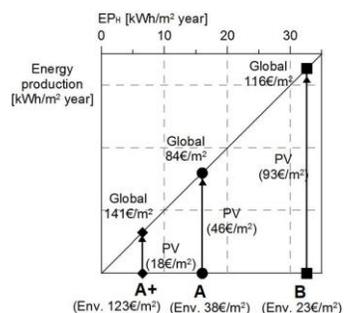


Figure 11. Cost comparison for different type of envelope solutions projecting the data in 20 years.

The same results can be achieved by projecting the data in 20 years (Figure 11). A price reduction of 20% of the PV modules price has been suggested and an increase of the envelope investment costs was calculated according to EN 15459 [16], that takes into account the trends.

This case also shows that a class A envelope is a reasonable trade off in terms of global costs.

CONCLUSION AND FUTURE WORK

The numerical investigation here presented allows to draw some conclusions about the design strategies that may be adopted to achieve cost optimality and NZEB performances for the investigated case study, which represents a large part of the building stock of Northern Italy:

1. The U value of the roof and walls is the design parameter that mostly affects the energy response of the building in terms of annual energy demand.
2. In case in which any PV renewable energy is adopted, the cost optimal solution is the one with a primary energy demand of 28 kWh/m²y (H+C).
3. In the case of renewable energy supply by means of PV panels, the envelope solution that guarantees, in any case, the cost optimality is characterized by an EP_H equal to 16 kWh/m²y, typical of a class A according to the energy rating of Lombardy Region.
4. Class A according to the energy rating of Lombardy Region is the most promising solution to reach net zero energy performance. As a matter of fact both more (A⁺) and less (B) performing envelopes require higher global costs to reach the NZEB standard.

Further analysis are in progress in order to extend the results to different building aspect ratios (Surface/Volume) and to investigate the role of the ratio between envelope surface and available surface for PV panels in defining the cost optimal solution.

ACKNOWLEDGMENT

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REFERENCES

- [1] The Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union, 53, 2010.
- [2] Regional law number 7 of 18th April 2012. "Misura per la crescita, lo sviluppo e l'occupazione". Official Journal of Lombardy Region (Italy).
- [3] J. Kurnitski, F. Allard, D. Braham, G. Goeders, P. Heiselberg, L. Jagemar, R. Kosonen, J. Lebrun, L. Mazzarella, J. Railio, O. Seppänen, M. Schmidt and M. Virta, "How to define nearly net zero energy buildings nZEB, REHVA proposal for uniformed national implementation of EPBD recast", REHVA Journal, May 2011, pp. 6 – 12.
- [4] A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori and A. Napolitano, "Zero energy building - A review of definitions and calculation methodologies", Energy and Buildings 43, 2011, pp. 971 – 979.
- [5] IEA SHC Task 40 / ECBCS Annex 52 'Towards Net Zero Energy Solar Buildings (NZEBs)', <http://www.iea-shc.org/task40/index.html> (retrieved: September, 2012)
- [6] A.J. Marszal and P. Heiselberg, "Life Cycle Cost analysis of a multi-storey residential Net Zero Energy Building in Denmark", Energy 36, 2011, pp. 5600 – 5609.
- [7] K. Voss, E. Musall and M. Lichtmeß, "From low-energy to net zero-energy buildings: status and perspectives", Journal of Green Building, Volume 6, Number 1, 2011, pp. 46 – 57.
- [8] A.J. Marszal, P. Heiselberg, R. Lund Jensen, J. Nørgaard, "On-site or off-site renewable energy supply options? Life cycle cost analysis of a Net Zero Energy Building in Denmark", Renewable Energy, 44, 2012, pp.154– 165.
- [9] J.Kurnitski, A. Saarib, T. Kalameesc, M. Vuolle, J. Niemelä, T. Tarke, "Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation", Energy and Buildings 43, 2011, pp. 3279–3288.
- [10] A. Hasan, M. Vuolle and K. Sirén, "Minimisation of life cycle cost of a detached house using combined simulation and optimisation", Building and Environment 43, 2008, pp. 2022 – 2034.
- [11] N. Doust, G. Masera and M. Imperadori, "A study on Design Optimization of a Near Net-Zero Energy House", Proceedings of the XVIII IAHS World Congress on Housing Science, 2012, Turkey.
- [12] TRNSYS 16. A Transient Simulation Program. University of Wisconsin, Madison, WI.
- [13] C. Adam and P. Andre. "Validation exercise applied to some TRNSYS components in the context of IEA 34/43." Paper presented at EPIC 2006 AIVC. Lyon, France, novembre 2006.
- [14] M. Wetter, "GenOpt, generic optimisation program, user manual", version 2.0.0. Technical report LBNL-54199, Lawrence Berkeley National Laboratory, 2004. Manual and program downloadable free of charge from <http://gundog.lbl.gov/GO> (retrieved: September, 2012)
- [15] A. Hasan, "Optimal design of Net Zero Energy Buildings", Low-Energy Architecture (LEA), World Renewable Energy Congress 2011, Sweden.
- [16] EN 15459, Energy performance of buildings – economic evaluation procedure for energy systems in buildings, November 2007.
- [17] Commission Delegated Regulation No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU) on the energy performance of buildings.
- [18] The Buildings Performance Institute Europe (BPIE), "Cost optimality: Discussing methodology and challenges within the recast Energy Performance of Buildings Directive". http://dl.dropbox.com/u/4399528/BPIE/BPIE_costoptimality_publication2010.pdf (retrieved: September, 2012).
- [19] A.N. Celik and N. Acikgoz, "Modelling and experimental verification of the operating current of mono-crystalline photovoltaic modules using four- and five-parameter models", Appl Energy 84, 2007, pp.1–15.
- [20] J.A. Duffie and W.A. Beckman, "Solar Engineering of Thermal Processes", 2nd Edition, John Wiley & Sons, Inc., New York. 1991.
- [21] J. Nelson, The Physics of Solar Cells, Imperial College Press, 2003, London.
- [22] W. De Soto, S.A. Klein and W.A. Beckman, "Improvement and validation of a model for photovoltaic array performance", Solar Energy, 80, 2006, pp.78–88.
- [23] <http://www.sunpowercorp.co.uk/commercial/products-services/solar-panels/e20/> (retrieved: September, 2012)
- [24] <http://www.conto-energia-online.it/> (retrieved: September, 2012).